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LIMITS OF COMPLETE INFLAMMABILITY OF MIXTURES OF MINE GASES AND OF INDUSTRIAL GASES WITH AIR

BY

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THE LIMITS OF COMPLETE INFLAMMABILITY OF MIXTURES OF MINE GASES AND OF INDUSTRIAL GASES WITH AIR.

By GEORGE A. BURRELL and ALFRED W. GAUGER.

INTRODUCTION.

This report summarizes the results of numerous experiments to determine the limits of inflammability of mixtures of mine gases and of industrial gases with air. The general investigation was undertaken by the Bureau of Mines in connection with its activities to increase safety in mining and the allied mineral industries. Details of the experiments on the limits of inflammability of gases can be found in Bureau of Mines publications.[a]

RESULTS.

The most important results of the inflammability experiments are shown in figure 1. The data are of importance in relation to the occurrence of inflammable gases in mines and to the industrial use of such gases. The gases investigated were gasoline vapor, ethane, methane, natural gas, acetylene, artificial illuminating gas, hydrogen, carbon monoxide, and blast-furnace gas. Vast quantities of gasoline vapor, natural gas, acetylene, artificial illuminating gas, blast-furnace gas, and hydrogen are being utilized for industrial purposes. Methane, hydrogen, and carbon monoxide are found in mines. Methane and ethane are constituents of natural gas.

FLAME PROPAGATION IN GASEOUS MIXTURES.

Flame is said to be self-propagated through a mixture of combustible gas and air, or of combustible gas and oxygen, when enough of the combustible gas is present to permit combustion to spread through the mixture from any given point of ignition. Then propagation of flame takes place from layer to layer of the mixture without the continued presence of the source of heat that started the inflammation.

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[a] Burrell, G. A., and Oberfell, G. G., The explosibility of acetylene: Technical Paper 112, 1915, 15 pp. Burrell, G. A., and Boyd, H. T., Inflammability of mixtures of gasoline vapor and air: Technical Paper 115, 1915, 18 pp. Burrell, G. A., and Oberfell, G. G., The limits of inflammability of mixtures of methane and air: Technical Paper 119, 1915, 30 pp. Burrell, G. A., and Robertson, I. W., Effects of temperature and pressure on the explosibility of mixtures of methane and air: Technical Paper 121, 1916, 14 pp. Burrell, G. A., and Oberfell, G. G., Explosibility of gases from mine fires. 1915, 31 pp.

The conditions of experiment affect to some degree the limits of complete propagation. For instance, with mixtures of gasoline vapor and air, the low limit was 1.5 per cent when a mixture of vapor and air was ignited from the bottom upward and 2.0 per cent when ignition was made from the top downward. With methane, the limit was 5.50 per cent for horizontal propagation of flame and about 5 per cent when ignition was made from the bottom upward. In coal mines, where methane is found, the limits for horizontal propagation are the most important. In general, the limits are slightly lower when ignition occurs from the bottom upward than when it occurs from the top downward.

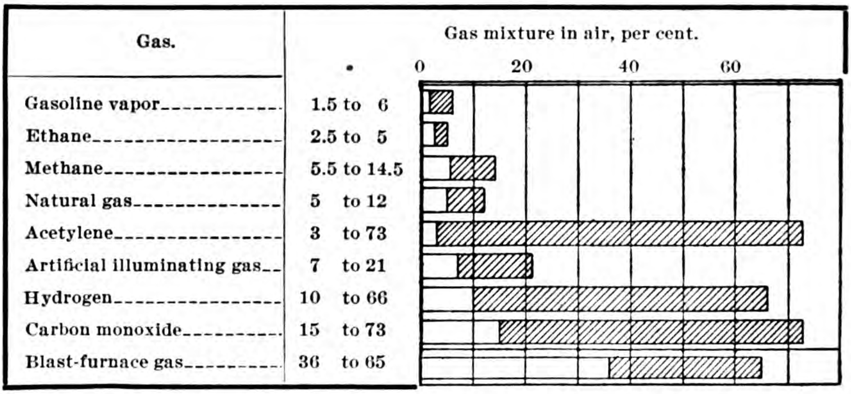

FIGURE 1.—Limits of complete inflammability of mixtures of combustible gases and air.

APPARATUS USED IN EXPERIMENTS.

In some of the experiments a glass vessel having a capacity of 2,800 c.c. was used as the container for the gases tested. Two copper wires entered through the sides and met at the center of the vessel. A current of 5 amperes at 15 volts was passed through the wires. Ignition of the gaseous mixtures was brought about by drawing the two wires apart while the electric current was flowing, thereby producing an electric flash.

CONDITIONS OF EXPERIMENTS.

In all of the author's experiments the explosion chamber was large enough so that its cold walls exerted no appreciable effect on the results. In spite of the slightly different results one can obtain under different conditions of experimenting, it is believed that the values for explosive limits given herein are close enough to be of decided commercial importance.

The results were obtained with gas mixtures kept at atmospheric pressure. The author found that with mixtures of methane and air and of gasoline vapor and air, raising the initial pressure to 6 atmospheres had no appreciable effect in changing the limits of complete inflammation, although the explosion, when it came, was of greater violence. As regards the effect of temperatures, raising the initial temperature from ordinary room temperature to as high as 200° C. only shifts the low limit for methane from 5.5 to about 5.05 per cent. Presumably increases of temperature and pressure affect to about the same degree the other gases mentioned in this report.

TESTS WITH ACETYLENE-AIR MIXTURES.

With a mixture of air and acetylene containing 2.81 per cent of acetylene, inflammation did not spread completely through the mixture. The flame traveled for 1 or 2 inches above the terminals but did not spread throughout the mixture. With 3.07 per cent of acetylene the flame spread entirely through the mixture.

TESTS WITH HYDROGEN-AIR MIXTURES.

With mixtures of hydrogen and air no propagation of flame could be noticed by the eye in mixtures containing 7 per cent of hydrogen when ignition was brought about by means of an electric spark from an induction coil driven by four small dry cells. But when the mixture was analyzed after sparking it was found that there had been a slight burning, undoubtedly only in the immediate neighborhood of the spark. As further experiments were tried with increasing percentages of hydrogen the amount of hydrogen that burned increased until, with 10 per cent hydrogen, it was completely burned.

TESTS WITH METHANE-AIR MIXTURES.

With mixtures of methane and air, the limits for complete propagation of flame were found to be between 5.5 and 14.5 per cent. With 5.5 per cent of methane the explosion was not violent. The flame could easily be followed by the eye. With larger percentages of methane—or any other inflammable gas—the explosions became more violent. At the lower limit the flame travels very slowly compared with its speed in richer mixtures.

The incomplete burning of mixtures of air and of combustible gases in proportions below the low limit is well shown by the miner's safety lamp as used in testing for methane in mine air. When a safety lamp is placed in air containing about 1.5 or 2 per cent of methane, a small cap is usually seen on the flame when the latter is turned low. Careful and experienced men may detect as little as 1 per cent of methane with a modern safety lamp. As the percentage of methane increases, the cap grows higher.

INCOMPLETE BURNING OF GASEOUS MIXTURES.

Incomplete burning also takes place in mixtures of air and of combustible gases in proportions above the upper limit. The upper limit for complete propagation of flame in mixtures of methane and air is 14.5 per cent. But even with a proportion of methane as high as 20 per cent, an electric flash about one-half inch long caused a slight burning, the flame extending about 3 inches above the electric flash. The explosion chamber used was 6 inches wide and 12 inches high. The igniter was placed in the center.

IMPORTANCE OF OXYGEN IN GASEOUS MIXTURES.

At present oxygen is used in increasing quantities for industrial purposes, hence the limits of inflammability of mixtures of combustible gases with oxygen are of immediate interest.

As regards methane-oxygen mixtures it was found that the low limit was raised about 0.25 per cent when pure oxygen was used instead of air. The high limit was, however, extended from 14.5 to 45 per cent methane, the explanation being as follows: In a methane-air mixture containing 9.47 per cent of methane and 90.53 per cent of air there is enough oxygen for complete combustion of the methane to carbon dioxide and water vapor. But if more methane is present, carbon monoxide and hydrogen, products of incomplete combustion, result. This reaction takes oxygen that would otherwise form carbon dioxide and water vapor. Some heat is produced, but much more heat is produced in the formation of carbon dioxide and water. As the percentage of methane is increased above 9.47 per cent, more and more carbon monoxide and hydrogen are formed from combustion until so much is formed that not enough heat is produced by ignition of the gas molecules adjacent to the igniter to cause the mixture to propagate flame. As air is only about one-fifth oxygen, substituting oxygen for an equal volume of air greatly increases the proportion of oxygen available for burning the combustible gas, the gas burns to water vapor and carbon dioxide, the heat of combustion is greater, and the upper limit of propagation becomes higher.

Presumably the upper limits for other gases would also be extended if oxygen were used instead of air. However, the low limits are the important ones as regards danger of accidental explosions, and these are seemingly not much affected.

The values for explosive limits given in this report refer to mixtures of the combustible gases with nearly pure air having a normal oxygen content. However, the oxygen content has to fall considerably before the limits of complete inflammability are appreciably changed. For instance, for mixtures of methane and air the low limit is given as 5.5 per cent of methane, which is the limit when the oxygen content varies between 17 and 21 per cent. With 17 per cent of oxygen in the mixture, the limit is raised to 5.7 per cent of methane. The oxygen content has to fall below 14 per cent to prevent all explosions in mixtures of methane and air. Replacing the nitrogen of the air with 20 per cent carbon dioxide raises the limit to 6.4 per cent methane. Raising the pressure of a gas mixture above atmospheric has no appreciable effect in changing the explosive range.

The authors compressed mixtures of hydrogen and oxygen in a steel bomb to 100 atmospheres before ignition and found that the explosive range was only a trifle different than the range at at atmospheric pressure. The low limit was raised about 1 per cent.

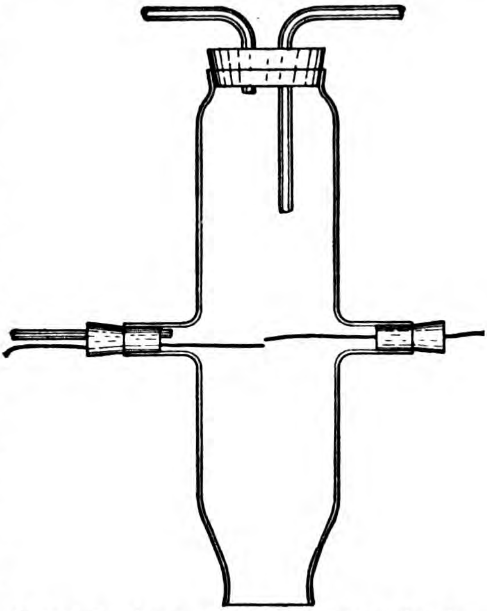

FIGURE 2.—Apparatus used in determining inflammability of mixtures of blast-furnace gas and air.

LIMITS OF INFLAMMABILITY OF MIXTURES OF BLAST-FURNACE GAS AND AIR.

Explosions have occurred at blast furnaces owing to the leakage of air into gas conduits and the subsequent ignition of the resulting mixture. The results of experiments to determine the explosive limits of mixtures of blast-furnace gas and air are presented below.

In the experiments a glass vessel of the shape shown in figure 2 was used. It was 8½ inches long and had a capacity of 900 c. c. A little above the center two copper electrodes were so arranged that they could be separated by the operator to produce an arc. The top was capped with heavy waxed paper. All experiments were made with the mixtures saturated with water vapor at room temperature and atmospheric pressure.

The blast-furnace gas used had the following composition:

Constituent.	Per cent.
Carbon dioxide	10.0
Oxygen	0.5
Hydrogen	2.7
Carbon monoxide	27.5
Methane	0.3
Nitrogen	59.0
	100.0

The results of the experiments follow:

Results of experiments to determine explosive limits of mixtures of blast-furnace gas and air.

Test No.	Percentage of blast-furnace gas in gas-air mixtures.	Remarks.
1	20.0	No ignition.
2	30.0	Do.
3	39.2	Do.
4	44.8	Do.
5	50.0	Ignited at once. Blue flame traveled upward and downward.
6	46.5	Ignited at once and blew cap off.
7	45.7	Do.
8	44.9	Small tongue of flame started at are and rolled to top. No complete inflammation.
9	56.1	Ignited at once and blew off cap.
10	57.0	Cap blown off.
11	61.0	Do.
12	62.0	Do.
13	72.0	No ignition.
14	67.9	Do.
15	65.0	Slight snapping ignition around arc. No complete inflammation.
16	64.5	Ignited at once and flame filled bottle.
17	66.0	No ignition.

The proportions of blast-furnace gas that mark the limits of inflammability of mixtures of air and blast-furnace gas of the composition given are 44.9 to 45.7 per cent for the low limit gas and 64.5 to 65 per cent for the high limit. Thus, in order to have an explosion of blast-furnace gas, not less than 35 cubic feet nor more than 55 cubic feet of air must be present in 100 cubic feet of a mixture of such gas with air.

The composition of iron blast-furnace gas varies considerably in practice. Below is a table, taken from Metallurgical and Chemical Engineering, volume 10, 1912, page 713, which was compiled from 860 different tests, covering a range of more than 20 furnace linings:

Table showing character of gases produced in blast furnace using natural air, with the corresponding coke consumptions.

Coke used per ton of metal.	Product.	CO_2.	CO.	H_2.	N_2.
Pounds.		*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
3,200-3,400	Spiegel	6.2	30.9	2.3	60.6
3,400-3,500	.....do	7.0	30.0	3.5	59.5
4,800	Ferrosilicon	3.5	32.5	2.0	62.0
5,300-5,400	Ferromanganese	4.6	32.6	1.2	61.6
5,400-5,500	.....do	3.6	32.2	2.2	62.0
5,500-5,600	.....do	5.0	28.0	2.6	64.4
5,700	.....do	3.4	33.8	2.4	60.4
5,800	.....do	4.3	33.1	1.7	60.7
5,900	.....do	3.8	32.9	2.4	60.7
6,000	.....do	5.0	34.4	2.7	57.9
6,100	.....do	3.0	31.2	2.0	61.8
6,500	.....do	4.4	30.8	2.2	62.6
7,503	.....do	3.6	32.4	2.4	61.6
2,100-2,200	Bessemer iron	13.1	24.1	1.7	61.1
2,200-2,300	.....do	12.1	23.9	2.0	61.9
2,300-2,350	.....do	11.8	25.6	2.1	60.5
2,350-2,400	.....do	11.8	24.8	1.9	61.4
2,400-2,450	.....do	11.7	25.4	1.4	61.5

Stoughton[a] gives the average composition for iron blast furnace gas as about 61 per cent nitrogen, 10 to 17 per cent carbon dioxide, and 22 to 27 per cent carbon monoxide.

The maximum variations in the composition of blast-furnace gas are apparently in the percentages of carbon dioxide and carbon monoxide. If 45.5 per cent of gas be taken as the lower limit of the gas, then the limit mixture contained 12.5 per cent carbon monoxide, 1.2 per cent hydrogen and 11.6 per cent oxygen. Should the carbon monoxide content drop to 22 per cent and the carbon dioxide content increase to 17 per cent, the hydrogen and nitrogen contents remaining approximately the same as before, then 56.8 per cent gas will be required before 12.5 per cent carbon monoxide will be present.

If the percentage of carbon monoxide should increase then the lower limit of such a gas would be lower than 45.5 per cent. The maximum per cent of carbon monoxide in the table is 34.4 per cent. Of this gas 36.3 per cent would furnish 12.5 per cent carbon monoxide.

The upper limit, however, would not be changed appreciably, as it depends on the percentage of oxygen present which in turn depends on the percentage of air. For pure carbon monoxide the high limit is only 73 per cent, for pure hydrogen 66 per cent.

The lower limit for blast-furnace gas in general, therefore, varies with the amount of combustibles present in the gas from 36 to 57 per cent gas. The upper limit will, however, be approximately 65 per cent gas for all gases.

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[a] Stoughton, Bradley, Metallurgy of iron and steel, 1st ed., 1908, p. 30.

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